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When digital stereo correlation methods are used to generate elevation data from stereo images of the terrain, the likelihood that the correlation process will be successful throughout the whole of the stereo model can be enhanced significantly by using hierarchical, multi-scale, pyramidal, coarse-to-fine, etc., techniques. One main advantage of these techniques is that the correlation data obtained at a lower resolution in the hierarchical procedure is used to guide and control the correlation process at the next higher resolution and, consequently, the user can be reasonably assured that the correlation process will not get "lost."

Unfortunately, constraints imposed by results obtained at the lower resolution can also lead to generation of erroneous elevation data in some circumstances. For example, if the terrain is spotted with individual trees, buildings or other structures, the correlation process, when performed on the low resolution images, will include approximations to the heights of these features in the resulting elevation data. These are erroneous elevations compared to the "bald earth" and their influence will be carried from one step to the next in the hierarchical procedure. The result will be a "noisy" digital elevation model (DEM) containing approximations to the elevations of trees and structures on the terrain and not just the terrain itself.

"Noisy" elevation data can be minimized as necessary by using non-hierarchical techniques such as "full-resolution" correlation or the "Iterative Orthophoto Refinements (IOR)" method.

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Alternatives to hierarchical techniques in stereo correlation

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ABSTRACT

When digital stereo correlation methods are used to generate elevation data from stereo images of the terrain, the likelihood that the correlation process will be successful throughout the whole of the stereo model can be enhanced significantly by using hierarchical, multi-scale, pyramidal, coarse-to-fine, ~~etc~~, techniques. One main advantage of these techniques is that the correlation data ~~obtained at a lower resolution in the~~ hierarchical procedure is used to guide and control the correlation process at the next higher resolution and, consequently, the user can be reasonably assured that the correlation process will not get "lost."

Unfortunately, constraints imposed by results obtained at the lower resolution can also lead to generation of erroneous elevation data in some circumstances. For example, if the terrain is spotted with individual trees, buildings or other structures, the correlation process, when performed on the low resolution images, will include approximations to the heights of these features in the resulting elevation data. These are erroneous elevations compared to the "bald earth" and their influence will be carried from one step to the next in the hierarchical procedure. The result will be a "noisy" digital elevation model (DEM) containing approximations to the elevations of trees and structures on the terrain and not just the terrain itself.

"Noisy" elevation data can be minimized as necessary by using non-hierarchical techniques such as "full-resolution" correlation or the "Iterative Orthophoto Refinements (IOR)" method.

1. INTRODUCTION

Digital stereo correlation is becoming widely accepted as a viable tool for generating digital elevation models (DEM's) from digital stereo images of the terrain. This observation is based on the fact that (1) most photogrammetric work stations include an automatic stereo correlation capability, (2) the number of published articles on the subject is on the rise and (3) some large government mapping agencies and private companies are acquiring extensive capabilities to perform digital correlation in a production environment.

The dramatic increases in computer processing rates over the past 20 years accounts for much of the acceptance of stereo correlation. On the one hand, DEM's can now be generated at rates exceeding conventional compilation methods. On the other, modern computer rates allow the developer to include compute-intensive algorithms and refinements in the correlation software that makes it more user-friendly and more responsive to the user's requirements.

One of the more important developments in stereo correlation algorithms is the technique variously described as hierarchical, multi-scale, pyramidal or coarse-to-fine processing. It is important because it maximizes the probability of correlation success over the whole stereo model by providing an effective means for initiating and controlling the correlation process.

In this technique, the original stereo images are reduced in scale and resolution often by successive factors of two. The smallest images are correlated first to provide approximate correlation data such as match points between images or elevations of the terrain. These approximate results are then interpolated in some manner to provide initial estimates for the correlation process at the next higher resolution.

If the terrain contains vertical features such as individual trees, small clumps of trees, building, etc., their heights may be approximated in the low-resolution step and be propagated through the successive steps in a hierarchical procedure. This could result in a DEM containing erroneous elevations compared to the "bald earth." In such cases, alternatives to the hierarchical technique should be considered.

One alternative is to perform correlation only on the full-resolution images. If a correlation method allows it, the user can construct "starting profiles" in a full-resolution stereo model to initially constrain the correlation process. One profile would, for example, be drawn across the top of the stereo model and one along the left edge. They would be drawn through, rather than over, the undesirable vertical features and thus constrain the correlation process, at least initially, to treatment of terrain points only. If "tuning" parameters in the correlation software, such as the minimum acceptable figure-of-merit and the maximum allowed x-parallax detection ("pull-in" range), are set "tight" enough, correlation on the images of vertical features will fail to produce acceptable results. The coordinates of these undesirable points can then be replaced by interpolation across points that are acceptable, thereby eliminating them from the resulting DEM.

A second alternative to the hierarchical technique is the "Iterative Orthophoto Refinements (IOR)," method[1]. The IOR method has been developed by U. S. Army Topographic Engineering Center (TEC), Fort Belvoir, Virginia, to edit and/or generate DEM's. The advantage of the IOR method is that it functions well with "tight" correlation "tuning" parameters and, therefore, is well suited for cases where the user wishes to minimize the effects of vertical features in a DEM.

TEC has performed tests on a stereo pair of digital images to compare the elative merits of hierarchical techniques and two non-hierarchical alternatives. The tests were performed on terrain images containing significant vertical features such as individual trees, small clumps of trees and areas of forest where the terrain can be viewed through the trees. TEC's correlation software, "match," was used in all tests. It is described briefly in the next section along with the IOR method. This is followed by descriptions of the test images, the tests performed and results obtained. A discussion of the results is then given followed by concluding remarks.

2. "MATCH" AND THE "IOR" METHOD

2.1 The correlation software, "match"

The correlation software used to conduct the tests is named "match." It is the off-spring of a program named the "Digital Interactive Mapping Program (DIMP)" which was developed by TEC in the late 1970's. DIMP was written in FORTRAN for a CDC computer and served for many years as TEC's research tool for conducting correlation experiments and for generating elevation data in support of other research projects. Later the DIMP algorithm, with many improvements and changes, was programmed in C-language for Silicon Graphics Iris 4D engineering work stations and renamed "match." A complete description of "match" is beyond the scope of this paper. The reader is referred instead to previous publications on the subject.[2,3]

"Match" is an area-based digital correlation method that operates in image space and is referenced to an evenly spaced grid of points on the left image of a stereo pair. That is, for equally spaced image points (grid) on the left image, "match" attempts to determine the coordinates of the corresponding points on the right image. The conjugate match points are later intersected to obtain x, y and z-ground coordinates for the points. These coordinates are them resampled to provide elevations at some uniform spacing in the desired ground coordinate system. Since "match" was written originally for research applications, the user is given wide latitude in the selection of algorithm options to use (ie., hierarchical procedure or not) and control over correlation "tuning" parameters (correlation window size, "pull-in" range, etc.) A summary of some features of the "match" routine is given in terms of keywords as follows:

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[1] F. Raye Norvelle, "Using Iterative Orthophoto Refinements to Correct Digital Elevation Models (DEM's)", ASPRS Proc., Vol. 2, pp.27-35, Aug 1992.

[2] F. Raye Norvelle, "Stereo Correlation: Window Shaping and DEM Corrections," Vol. 58, No. 1, pp. 111-115, Jan. 1992.

[3] F. Raye Norvelle, "Interactive Digital Correlation Techniques for Automatic Compilation of Elevation Data," ETL-0272, U. S. Army Engineer Topographic Laboratories, Fort Belvoir, Va., 1981.

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- Area correlation
- Match point interpolation
- Draw "starting profiles"
- User interaction
- Figures of merit
- Match point prediction
- Two-dimensional correlation
- 3-D Display of results
- Window shaping
- Hierarchical procedures
- Variable area compilation
- Normalized cross correlation

2.2 The IOR method

The "match" routine described above is very accurate but the DEM obtained from the correlation results will not be without error. Consequently, the "match" results must be edited, and this can be a tedious and time-consuming endeavor. To minimize, if not eliminate, the need for editing, TEC developed the IOR method. It performs very well and is no longer considered just an editing tool but a DEM generation method as well. The IOR method is based on the premise that, given an accurate DEM and known orientation and position data for a stereo pair of terrain images, orthophoto images made of both the left and right mates of the original stereo images should be geometrically identical. If they are not, the mismatches are due to errors in the DEM. These mismatches can be measured automatically with the "match" routine and converted to equivalent elevation errors. The elevation errors are then subtracted from the current DEM. The improved DEM is used to generate new orthophoto images and the correction process is repeated. The IOR procedure is iterated in this manner until mismatches are eliminated and, consequently, the DEM is corrected in the process.

When sloping terrain surfaces are photographed by a camera from different positions, the terrain surface will be imaged on the two photographs with different shapes and sizes. These differences are a chief cause for errors made by a correlation routine, such as "match," even though an effort may be made to correct the differences (window shaping) during the correlation process. When orthophoto images are generated, the dissimilarities between images are practically removed. Consequently, a correlation method can often perform more accurately on the orthophoto images than on the original stereo images themselves.

If the dissimilarities are small, a small "pull-in" range can be used in the "match" routine which minimizes the probability of false "match" results. In the context of this paper, a small "pull-in" range also helps to prevent the correlation routine from obtaining the heights of unwanted vertical features.

3. THE IMAGES

Figure 1a shows an overview of the Grayling, Michigan area along with two enlarged subsets of an excavated area (Figure 1b) and a sparse forest area (Figure 1c.) The original stereo photographs have a scale of approximately 1:12000. They were digitized with a 30-micrometer spot size which equates approximately to a 0.36-meter ground sample distance. Each image of the stereo pair has a size of 3890 x 6890 pixels.

The terrain is characterized by a sparse forest in the lower left corner of the stereo model and a smaller, dense forest area in the upper right corner. The ground surface can be seen through the trees in the sparse forest areas and the shadows of the trees on the ground provide gray shade variances that aid the correlation process. The forest trees are approximately 10 meters tall. The rest of the terrain is mostly dotted with individual trees about 6 meters tall on otherwise bare ground. There are several man-made embankments and excavations with slopes up to 35 degrees and slope changes up to 60 degrees. For the most part, the terrain is gently rolling with elevations ranging between 349 and 392 meters above sea level.

4. DESCRIPTION OF TESTS

Three tests were performed with the Grayling stereo images. In the first test, a hierarchical approach is used to generate a DEM. In the second, the DEM is generated from data obtained by correlation on the full-resolution images only. In the third, the IOR method is used to create the DEM. Descriptions of the test methods are given in the following sections.

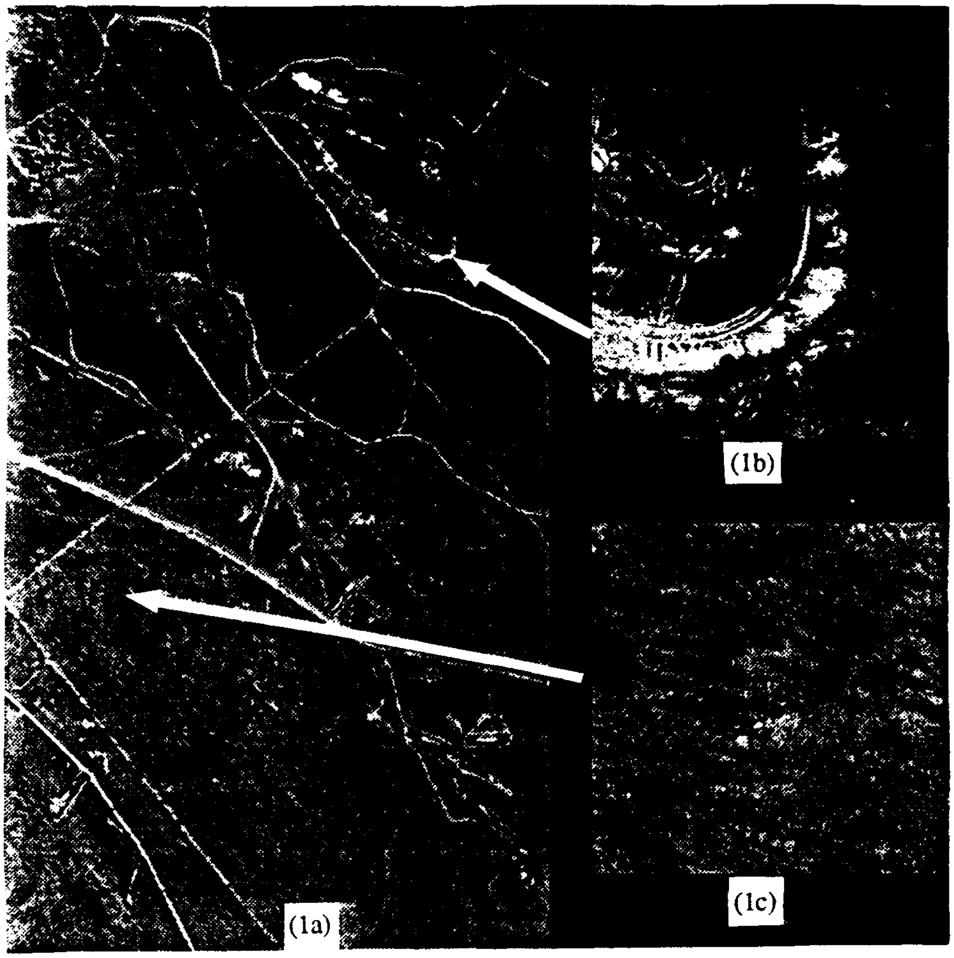


Figure 1. (a) Test image of Grayling, Michigan area. (b) Enlargement of excavated area.
(c) Enlargement of sparse forest.

4.1 Hierarchical procedure

The original stereo images were reduced in size by 1/8, 1/4 and 1/2 using simple pixel averaging. First, the 1/8x images were correlated at every 10 pixels on the left image to obtain conjugate image points (match points) on the right image. These were then expanded by a factor of 2, using bilinear interpolation, and used as predicted match point positions for correlation at every 10 pixels on the 1/4x images. This procedure was repeated in successive steps until the full-resolution images had been correlated.

The user plotted the corners of the desired compilation area in the 1/8x stereo model and entered the "tuning" parameters for "match." Thereafter, no further user inputs were required. In each step of the hierarchical procedure, correlation on each point was performed by comparing a 17 x 17-pixel "window" of gray shades from the left image to a 19 x 25-pixel "search area" on the right image. This allowed for a "pull-in" range, relative to the predicted position of the match point on the right image, of ±4 pixels in the x-parallax direction and ±1 pixel in the y-parallax direction.

If the figure of merit computed for each matched point did not exceed a "moderate" threshold, the point was deemed unacceptable. After each row of correlations, the coordinates of unacceptable match points were replaced by straight line interpolation across acceptable points.

The final match point coordinates were intersected to provide corresponding x, y and z-ground coordinates in a local space rectangular coordinate system. Bilinear interpolation was used to resample the ground coordinates into a DEM with a 5-meter spacing between elevation "posts."

4.2 Full-resolution correlation

This test is basically the same as the hierarchical test except correlation was performed only on the full-resolution stereo images without reliance on any previously derived correlation data. Unlike the hierarchical approach, the user constructed "starting profiles" across the top of the stereo model and down the left side. This process outlines the compilation area and provides initial estimates for the coordinates of match points on the right image that correspond to the equally spaced points on the left image. The "starting profiles" were drawn through, rather than over, the vertical features and thereby constrained the correlation process to treatment of terrain points only. The "tuning" parameters such as window size, "pull-in" ranges, required figure of merit, etc., were identical to those used in the hierarchical test.

4.3 IOR method

The match point coordinates obtained by correlation on the 1/8x images in the hierarchical test were used in this test to derive an approximate DEM. At the 1/8x scale, a pixel is equivalent to about 2.9 meters on the ground. Since the reduced images were correlated at every 10 pixels on the left image, the corresponding ground coordinates have a spacing of about 29 meters. These were re-sampled to provide an approximate DEM with the desired 5-meter spacing.

The initial DEM was used to generate orthophoto images of both the left and right mates of the original stereo images. The size of each orthophoto was 2441 x 4691 pixels where each pixel had a 0.5-meter ground sample distance (gsd.) "Match" was used to determine the mismatches (x-parallax) between the orthophoto images. The mismatches were converted to equivalent elevation errors and subtracted from the initial DEM.

Correlation on the orthophoto images was performed initially using a 17 x 17-pixel window and x and y-"pull-in" ranges of ±2 pixels and ±1 pixel. Correlated points had to receive a "high" figure of merit before they were considered acceptable.

Normally, the IOR method would be performed in an iterative manner. In this test, however, the first set of corrections to the DEM were sufficient, except in areas where man-made embankments presented special problems because of steep slopes and sharp slope changes. Theses areas were recompiled using a larger "pull-in" range (±4 pixels) in the x-parallax direction and a "moderate" threshold on the required figure of merit.

5. RESULTS

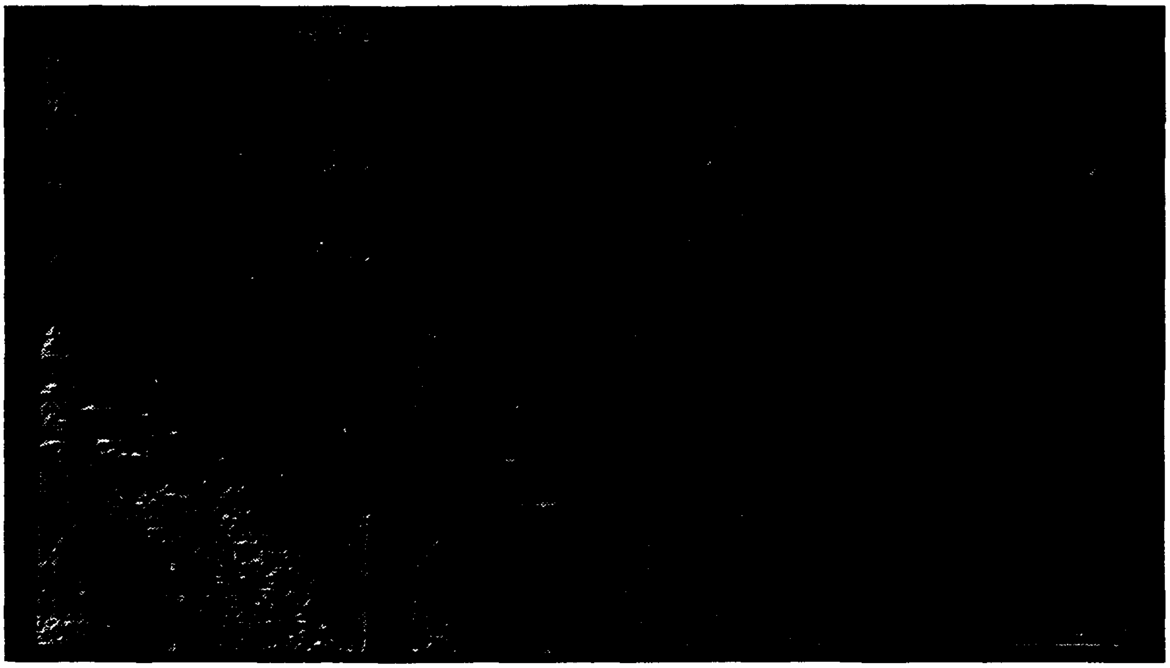
5.1 DEM comparisons

The results of the three tests are shown in Figure 2 as synthetic shaded relief images of the resulting 5-meter DEM's. The "sun" is in the upper-left corner of the DEM at an angle of 75 degrees from the vertical. Figures 2a, 2b and 2c refer to the results from the hierarchical, "full-resolution" and the IOR method. Note that on the DEM generated by the IOR method, a narrow strip around the edges contains the elevations of the original, approximate DEM. This strip is left uncorrected to insure that neither the correlation "window" nor the "search area" will extend past the limits of the image data.

5.2 Statistical Results

Table 1 gives a comparison of the statistics compiled by the "match" routine in the three tests. In the hierarchical and "full-resolution" tests, the number of points correlated are about equal. The number in the IOR method is much less than those in the other two tests because an orthophoto pixel is larger (0.5m gsd) than an image pixel (0.36m gsd) and fewer are required to cover the same area. The "R" coefficient is the average value of the normalized cross correlation coefficient which can range from 0 to 1. The average "dx" and "dy" values are the corrections, in pixels, made to the predicted coordinates of the match point on the right image. In the hierarchical test, the "predicted" coordinates come from interpolation of those acquired on the lower resolution images. In the other two tests, they are extrapolated from match point coordinates obtained above and to the left of the "next" point to be correlated. Unacceptable points are those that failed to meet the required figure of merit. The

required figure of merit for the hierarchical and "full-resolution" tests was "moderate," but was "high" (more stringent) for the IOR method.



(2a) (2b) (2c)

Figure 2. Digital Elevation Models (DEM's) obtained from the (a) hierarchical test, (b) "full-resolution" test, (c) IOR method.

Hierarchical Test	1/8x images	1/4x images	1/2x images	Full-Resolution
Total No of Pts	3569	13776	54116	214500
Unacceptable	1	59	1771	17526
Avg R	.885	.846	.783	.659
Avg dx	.233	.411	.446	.421
Avg dy	.123	.177	.224	.323

Full-Resolution Test	
Total No of Pts	213856
Unacceptable	16064
Avg R	.658
Avg dx	.351
Avg dy	.233

IOR Method (Orthophoto images)	
Total No of Pts	100128
Unacceptable	10675
Avg R	.749
Avg dx	.232
Avg dy	.155

Table 1. Correlation Statistics

5.3 Execution times

The amount of time required to perform the various steps in the three tests is shown in Table 2. The Silicon Graphics Personal Iris 4D/35 was the processor on which all tests were run. As noted above, the number of points correlated on the orthophoto images was less than those in the other tests.

		Hierarchical	Full-Resolution	IOR Method
Make (2)	1/8x images	1.2'	N/A	1.2'
	1/4x images	1.4'	N/A	N/A
	1/2x images	2.2'	N/A	N/A
Total		4.8'	N/A	1.2'
Correlate	1/8x images	0.8'	N/A	0.8'
	1/4x images	3.0'	N/A	N/A
	1/2x images	11.6'	N/A	N/A
	Full images	46.2'	55.5'	N/A
Total		61.7'	55.5'	0.8'
Generate 2 Orthophotos		N/A	N/A	10.5'
Correlate Orthophotos		N/A	N/A	23.5'
Re-compile Orthophotos		N/A	N/A	32.0'
Total		N/A	N/A	55.5'
Post Editing		?	?	?
Total		66.5	55.5	68.0'

Table 2. Comparison of execution times.

6. DISCUSSION OF RESULTS

6.1 DEM comparisons

A DEM of the terrain in the Grayling images should appear as a smooth, gently rolling surface, except for a few man-made embankments and excavations. But the DEM obtained with the hierarchical approach (Figure 2a) shows the presence of many vertical features. These are the heights of individual trees, small clumps of trees and forest areas, and they represent elevation errors when compared to the "bald earth." The errors exist because correlation on the 1/8x images successfully matched the tops of many trees and their influence was propagated throughout the hierarchical steps and into the resulting DEM. Not all of the trees were detected nor were their heights accurately measured. The tree elevations represent "noise" in the DEM rather than true heights of vertical features.

The DEM obtained using "full-resolution" correlation (Figure 2b) is mostly void of tree heights and is considered, therefore, to be of higher quality than the DEM from the hierarchical approach. In the "full-resolution" test, the operator constrained the correlation process to the terrain surface by drawing "starting profiles" through the unwanted vertical features. At full resolution, the x-parallaxes produced by the vertical features are outside the allowed "pull-in" range of the correlation method. Consequently, correlation results on these features fail to meet the figure of merit test and are deemed unacceptable. The coordinates of the unacceptable points are replaced by interpolation across acceptable points and the affect of the trees is, thereby, negated. This was not the case across the whole stereo model, however. As can be seen in Figure 2b, some individual trees and clumps of trees were successfully correlated and appear in the DEM. This is because the fairly large "pull-in" range (± 4 pixels), and the "moderate" required figure of merit, allowed for successful correlation on some of the unwanted features.

More unwanted vertical features could have been eliminated from the DEM of Figure 2b by using a smaller "pull-in" range and a "tighter" figure of merit. But then the correlation process would not have been as successful on those man-made embankments and excavations that exhibit steep slopes and sharp slope changes. The same argument can be made for the choice of "tuning" parameters used in the hierarchical test.

In the IOR method, a large "pull-in" range and a "moderate" figure of merit constraint are not needed for successful correlation on orthophoto images. Therefore, "tighter" controls can be used to further reduce the occurrence of the vertical features in the DEM. In this test, the initial DEM obtained by correlating on the 1/8x images was used to generate approximately correct orthophoto images. The 3-D error surface of the stereo pair of orthophotos was essentially flat. Therefore, a small "pull-in" range and a "high" figure of merit could be imposed on the correlation process used to measure orthophoto mismatches. The constraints were too "tight," however, to allow successful correlation on the trees. This, as illustrated in Figure 2c, provided a more accurate DEM than was obtained in the previous two tests.

It should be noted that the "tight" constraints imposed in the IOR method were not suitable for correlation in all parts of the orthophoto images. The mismatches between orthophoto images of steep banks, for example, required special consideration. These areas were recompiled on the pair of orthophotos using the same "moderate" constraints applied in the hierarchical and "full-resolution" tests. The small areas involved were essentially void of trees and, therefore, their potential influence upon the DEM was not an issue.

The shaded relief images in Figure 2 represent terrain slope intensities rather than elevation errors, although sharp intensity changes are a good indicator of elevation errors. To assess DEM accuracy, the match point coordinates derived by "match," were displayed as 3-D profiles overlaying the stereo model. Accuracy of the results could then be judged in 3-D by visual inspection.

6.2 Comparison of statistical results

A major advantage of the hierarchical procedure is that correlation on reduced versions of the original images can be performed very fast and usually very successfully because the influences of large x-parallaxes, occlusions, shadows, etc., are reduced by the minification process. This is clearly illustrated by the results (Table 1) obtained in the hierarchical test using the 1/8x images. Only 1 in 3569 correlations failed to exceed a "moderate" figure of merit. The good results on the 1/8x images practically assured correlation success in the higher-resolution steps.

At the full-resolution step in the hierarchical test, 8.2 percent of the correlated points were unacceptable. This is quite low for images containing individual trees and forest areas where the variances in gray shades are sub-optimal for correlation. The average corrections to the predicted match point coordinates are relatively high, however. Research by TEC has shown that the predicted match point coordinates obtained by interpolation of results obtained at a lower resolution are less accurate than those obtained by the point prediction scheme used in the "match" routine. Consequently, "dx" and "dy" corrections are usually larger in a hierarchical procedure and sometimes call for a larger x and y-"pull-in" range than would ortherwise be required. Note, for example, that the average "dx" and "dy" corrections obtained in the "full-resolution" test are significantly smaller than those obtained at the full-resolution step in the hierarchical test. Yet the average correlation coefficient (R) and the number of unacceptable points is about the same.

The average "R", "dx" and "dy" values obtained with the IOR method are much better than from the other two tests. Removal of image dissimilarities by the orthophoto transformation process accounts for the high normalized cross correlation coefficient, R. The flatness of the orthophoto error surface allows accurate extrapolation of predicted match point coordinates and, therefore, reduces the magnitude of the "dx" and "dy" corrections. The number of unacceptable points (10.7 %) is greater with the IOR method because, to reduce the probability of correlation on unwanted features (trees), the constraints imposed on the IOR method were more stringent than in the other tests.

Overall, the statistical results indicate that correlation was very successfully in all three tests, although successful correlation does not necessarily translate into accurate elevations in the DEM.

6.3 Comparison of execution times

As shown in Table 2, the "full-resolution" approach required the least amount of time (55.5') to generate the 5-meter DEM. Approximately 9 minutes of that time was used by the operator to enter the "tuning" parameters and to draw the "starting

profiles" across the top and down the left side of the stereo model. The actual amount of time spent performing correlation (at a rate of 77 pts/sec) in the "full-resolution" test was about the same as for the full-resolution step in the hierarchical test.

The IOR method required the most time to create a DEM, although there was not a large difference between the three. The time saved by correlating on fewer points, and with a smaller "pull-in" range, was more than offset by the amount of time needed to reinitialize the correlation process in order to recompile a few areas where steep slopes existed. About 8 minutes of the time attributed to "Correlate orthophotos" was actually used to draw "starting profiles" and enter "tuning" parameters. Because of the small "pull-in" range used in the IOR method, a correlation rate of 110 pts/sec was achieved.

None of the three DEM's were edited. That's the reason for the question marks in Table 2 for "Post-Editing." The DEM produced by the IOR method is actually corrected as part of the process. It would only require post-editing in those image areas where the variance in gray shades was sub-optimal for correlation and, consequently, mismatches between orthophotos could not be detected.

The DEM from the "full-resolution" test would require a substantial post-editing effort to remove the tree elevations from the data. Most areas could be edited by modelling small, local terrain surfaces with a bi-variate polynomial, thereby removing "noisy" data (individual tree heights) from the DEM. In the forest areas, however, only a time-consuming, manual method could be used. It is estimated that 2 hours of editing would be required to bring the "full-resolution" DEM to the same quality as the DEM obtained by the IOR method.

The vast majority of the elevation errors in the hierarchical DEM occurred in the forest areas. Practically all of these data would have to be edited manually and this would probably require at least 6 hours to accomplish.

Based on the superior accuracy of the DEM obtained using the IOR method, and the fact that a minimum of editing is required, the IOR method is considered the faster and more accurate of the three when applied to image scales and terrain conditions typified by the Grayling images. If the Grayling images had been at a small scale to begin with, the x-parallaxes produced by the tree heights would have been much less significant, and their influence on a DEM of reduced resolution would not have been an issue.

7. CONCLUSIONS

- Hierarchical-type processing techniques can enhance the probability of correlation success in stereo correlation methods.

- Successful correlation results do not necessarily translate into accurate elevation data of the "bald earth."

- Hierarchical-type approaches are not desirable for generating DEM's of the terrain from large scale images if the heights of unwanted features, such as individual trees and buildings, are significant.

- The "Iterative Orthophoto Refinements (IOR)" method can be used successfully in lieu of hierarchical-type procedures for DEM generation.